Forward neutron transverse single-spin asymmetry: from p+p to p+A

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PHENIX Collaboration

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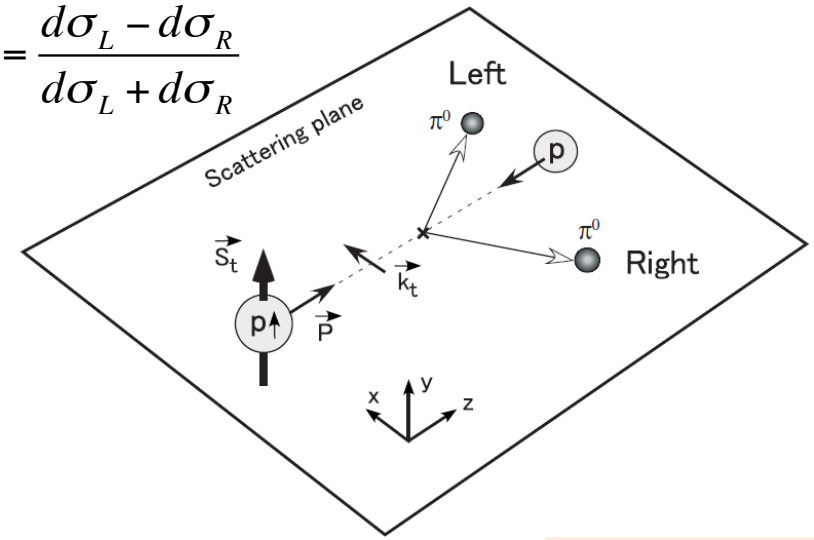
Outline

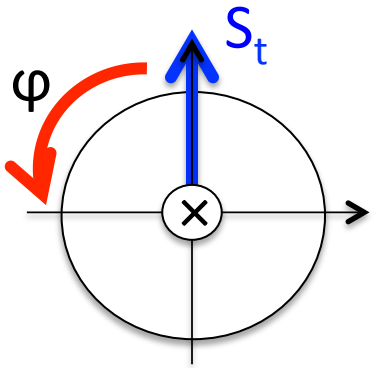
Transverse Single Spin Asymmetry: A_N

- A_N measurements and A_N for forward neutron production
- Forward neutron measurements at RHIC
- New results from RHIC Run2015: pp vs pA
- An attempt for physics interpretation
- Future measurements?

Transverse Spin Asymmetries A_N

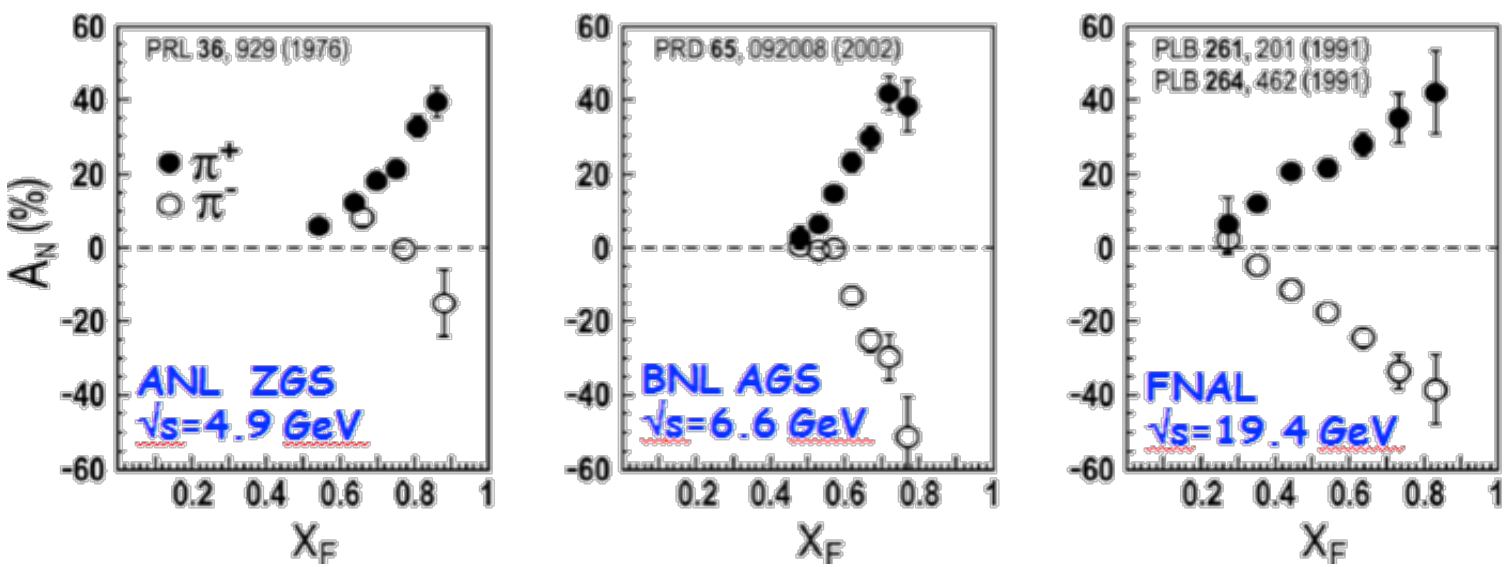
$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$





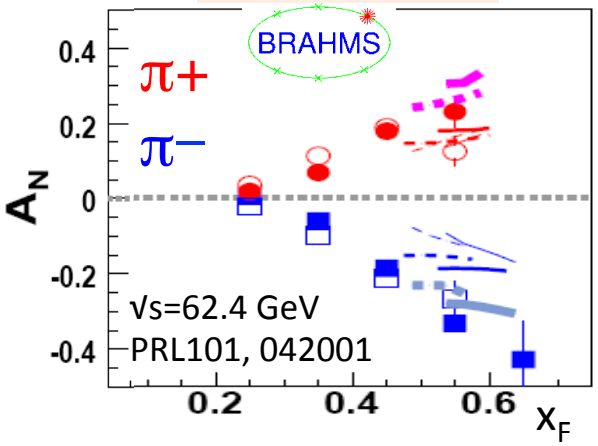
$$\frac{d\sigma}{d\varphi} = A + A_N \sin(\varphi)$$

Long history A_N measurements in pp

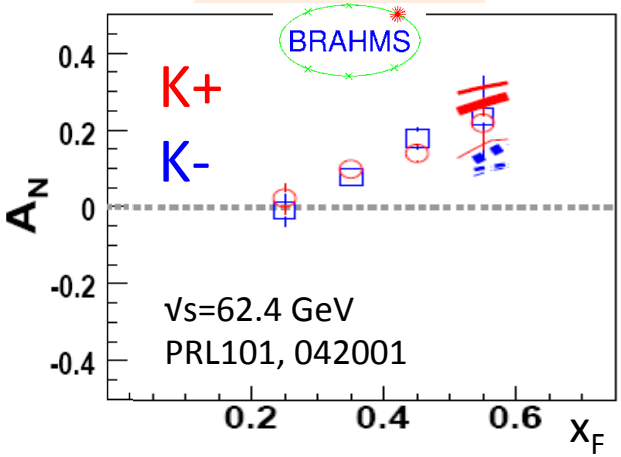


A_N at RHIC

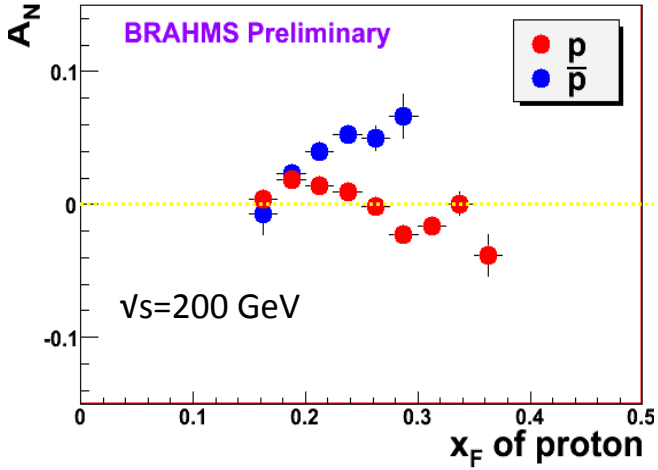
p+p -> $\pi^{\pm}$+X



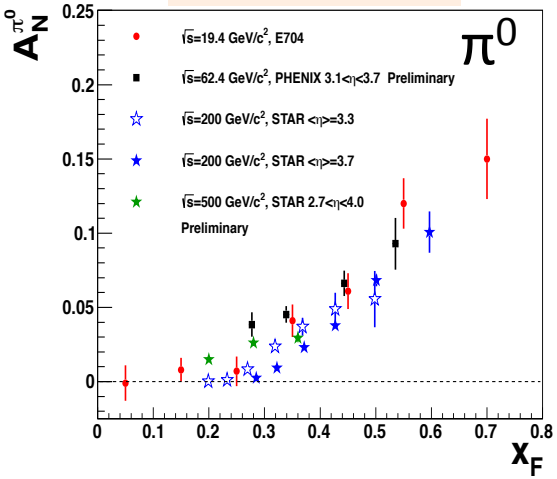
p+p -> $K^{\pm}$+X



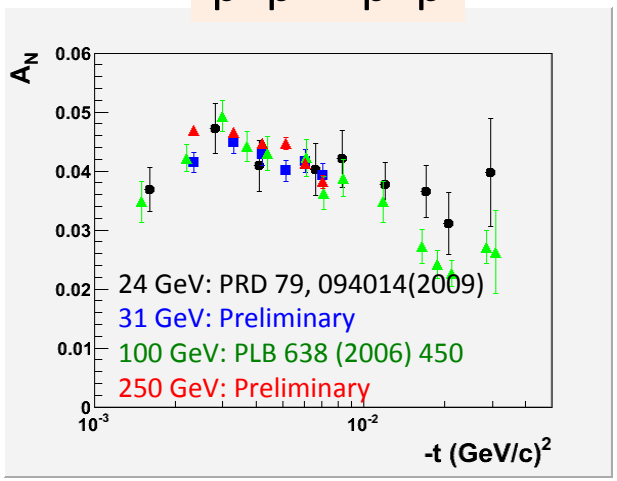
p+p -> p(bar)+X



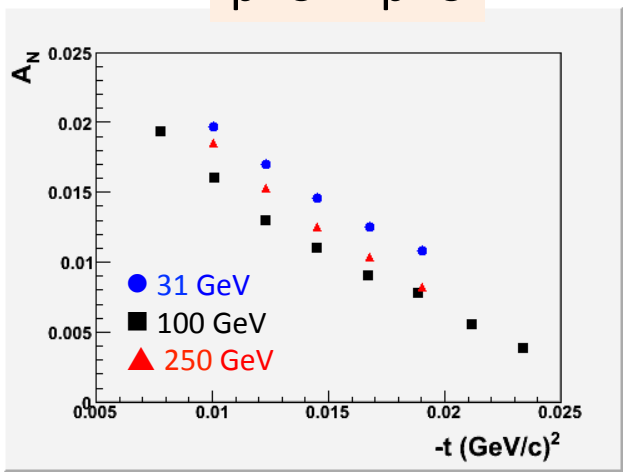
p+p -> π^0+X



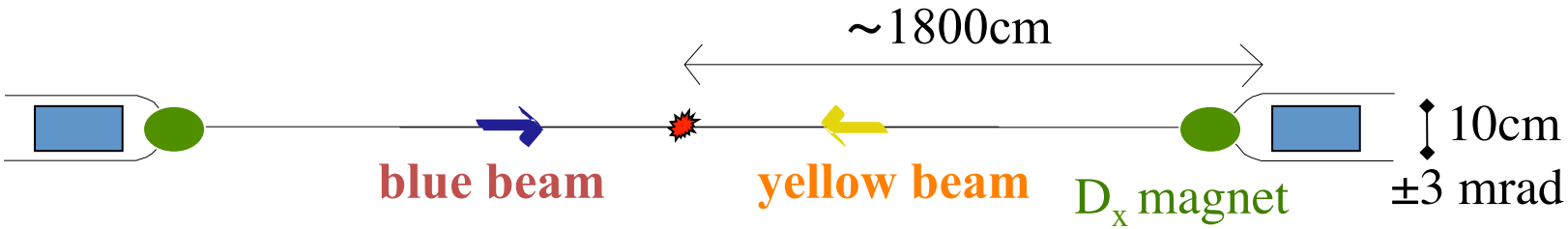
p+p -> p+p



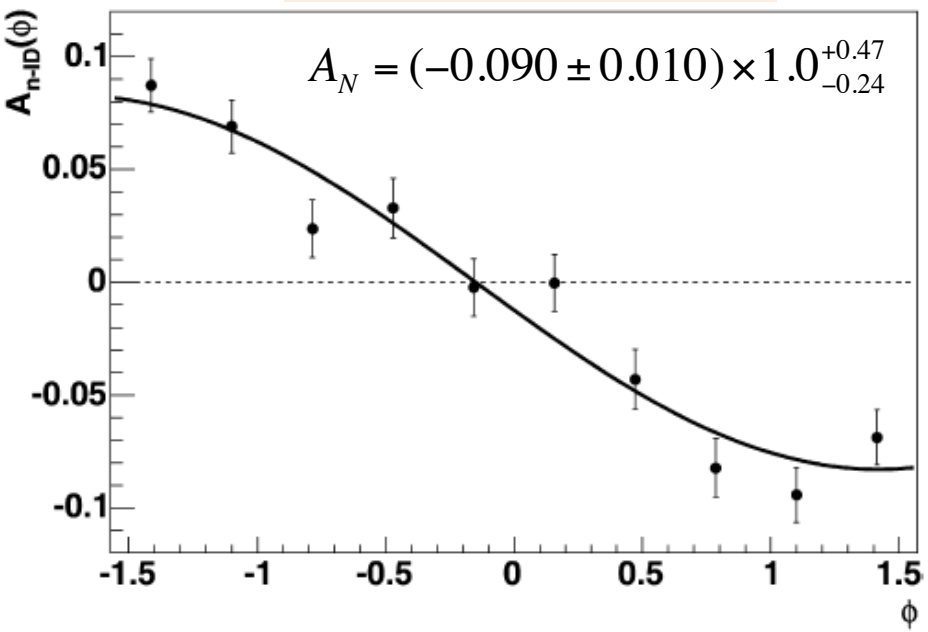
p+C -> p+C



Forward neutron A_N



PLB 650 (2007) 325.



Very first RHIC-Spin measurement

At IR12 from 2001-2002

An accidental discovery

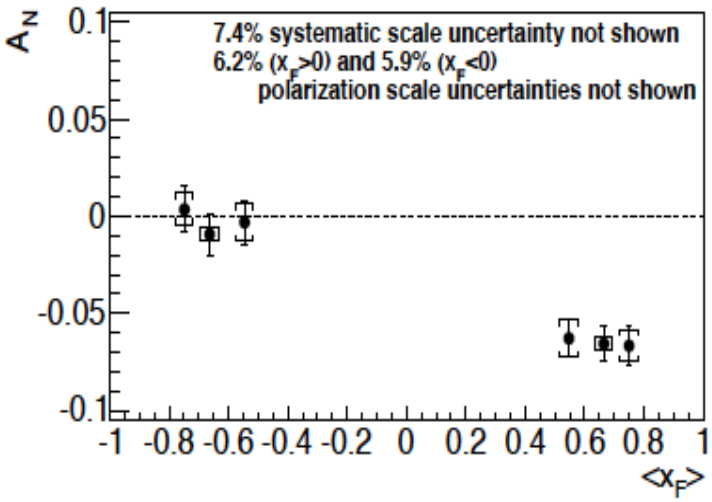
Were looking for π^0 asymmetry while developing Local Polarimeter

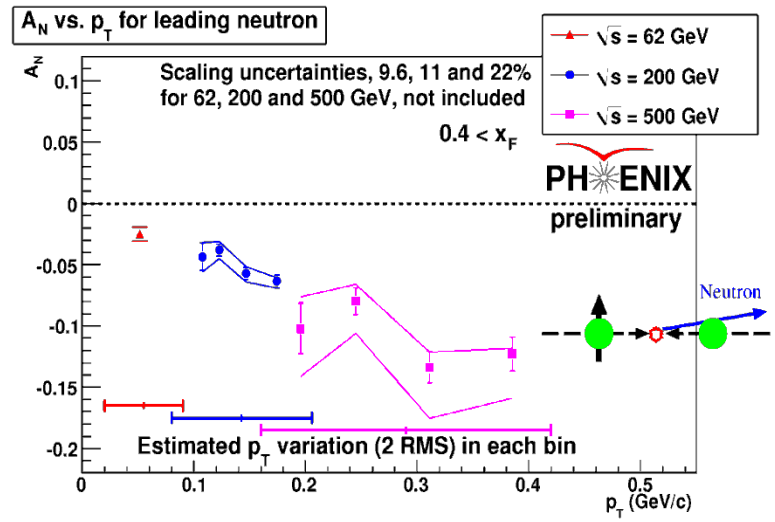
Discovery -> Calibration

Was immediately implemented for polarization measurements at IR (trans. component)

PHENIX: Forward neutron A_N

PRD 88 (2013), 032006





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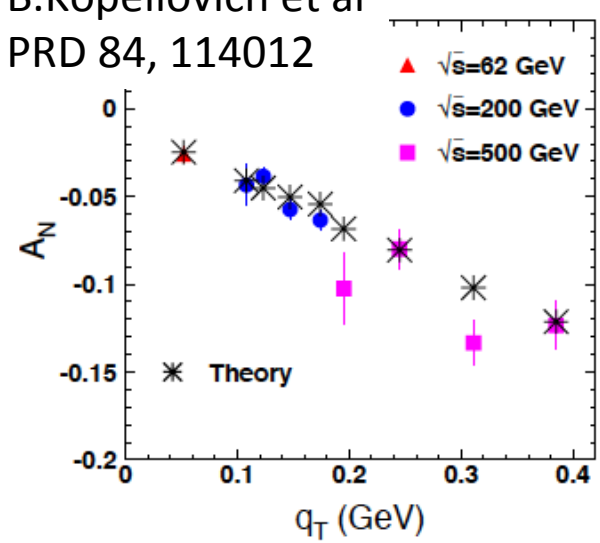
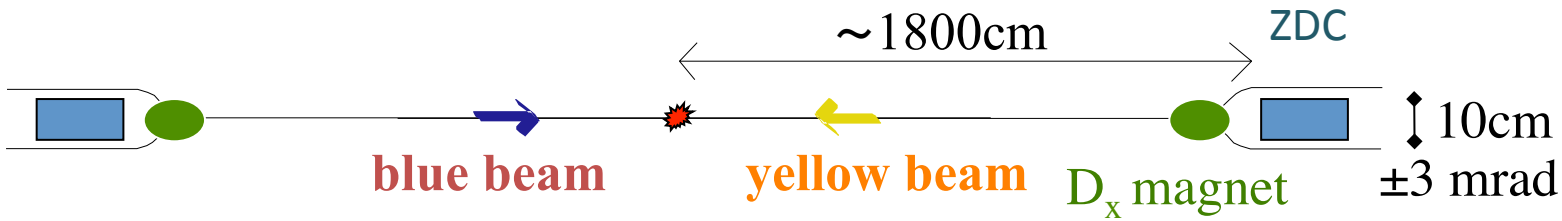


One pion Exchange model in Regge framework model
(interference between pion and a1-reggeon exchange)

Forward neutron measurements at PHENIX

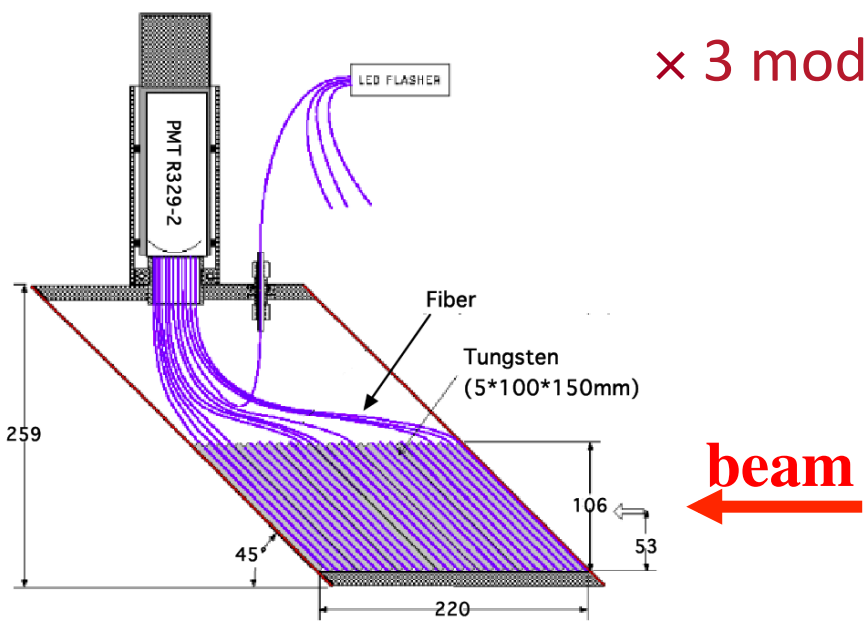
ZDC: Zero Degree Calorimeter



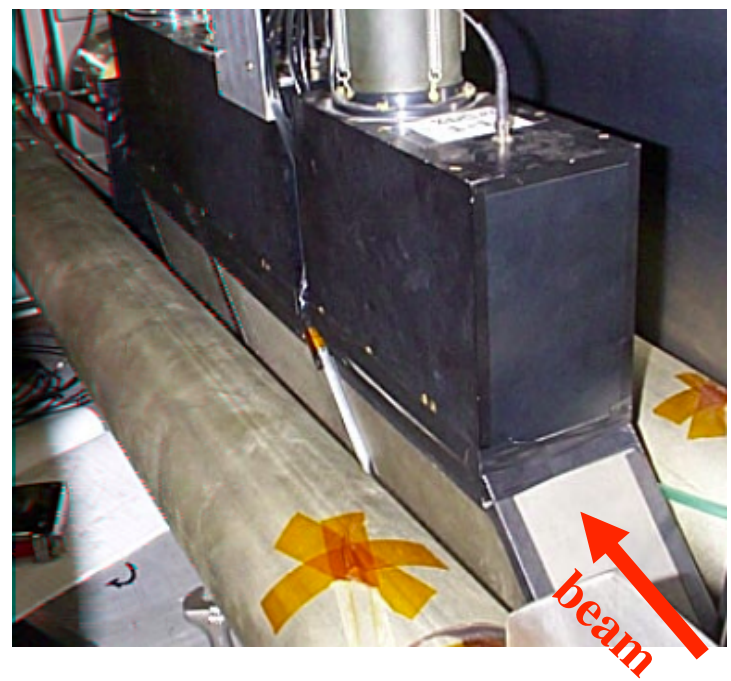
Hadron sampling calorimeter made of Tungsten plate and fibers

Detects neutrons and measure their energy

$5.1\lambda_T$ $149X_0$ (3 ZDCs), Energy resolution ~ 20% @ 100GeV



× 3 modules ➔



SMD: Shower Maximum Detector

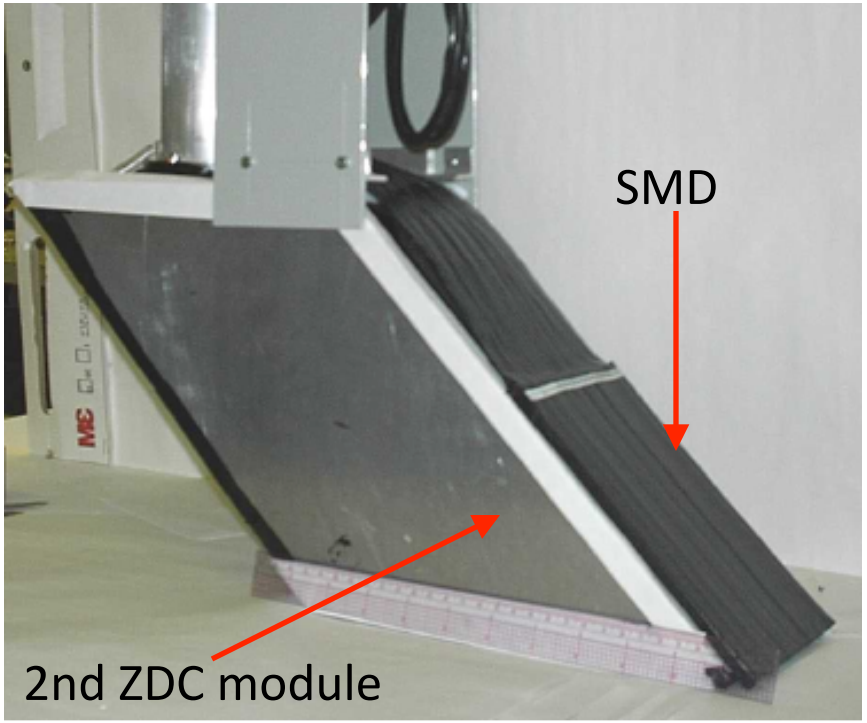
Arrays of plastic scintillators Installed between 1st and 2nd modules of ZDC

7 strips in X, 8 strips in Y

Measures neutron hit position

By calculating the center of gravity of shower generating in the 1st ZDC module

Position resolution ~1cm @ 100GeV neutron

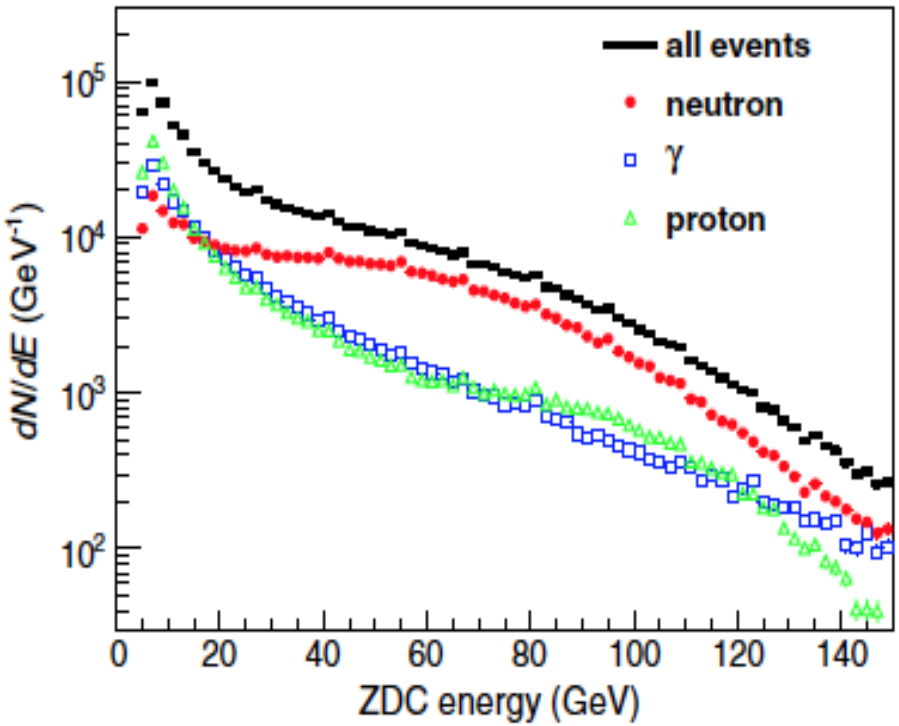


And charged veto

For charged background rejection

Neutron ID

ZDC energy response
from PYTHIA+GEANT



$40 < E_{ZDC} < 120$ GeV

Minimizes background contribution

Charged veto

Rejects charged background

No/little energy in ZDC-2

Suppresses photon background

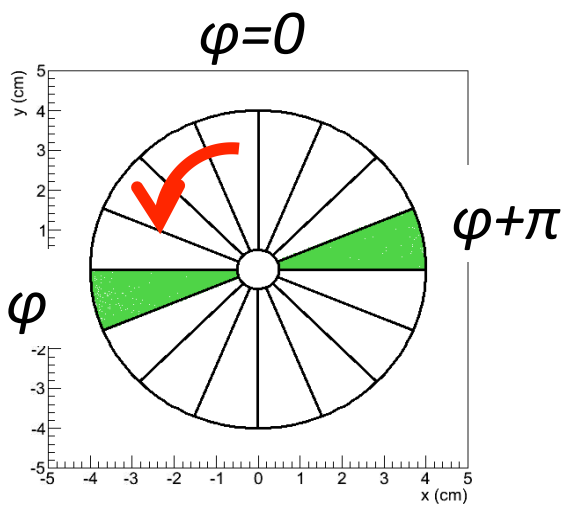
>1 SMD strip fired

Suppresses photon background

Neutron purity >97%

Residual background: protons, K^0

A_N Measurements



$$A = A(\varphi) = A_N \cdot \sin(\varphi)$$

$$N_L \text{ -> } N(\varphi)$$
$$N_R \text{ -> } N(\varphi+\pi)$$

- Detector Left-Right asymmetries or Spin Up-Down asymmetry

$$A_N = \frac{d\sigma_L^{\uparrow} - d\sigma_R^{\uparrow}}{d\sigma_L^{\uparrow} + d\sigma_R^{\uparrow}} = \frac{1}{P}\frac{N_L^{\uparrow} - R_{\det} N_R^{\uparrow}}{N_L^{\uparrow} + R_{\det} N_R^{\uparrow}}, \quad R_{\det} = \frac{\varepsilon_L}{\varepsilon_R}$$

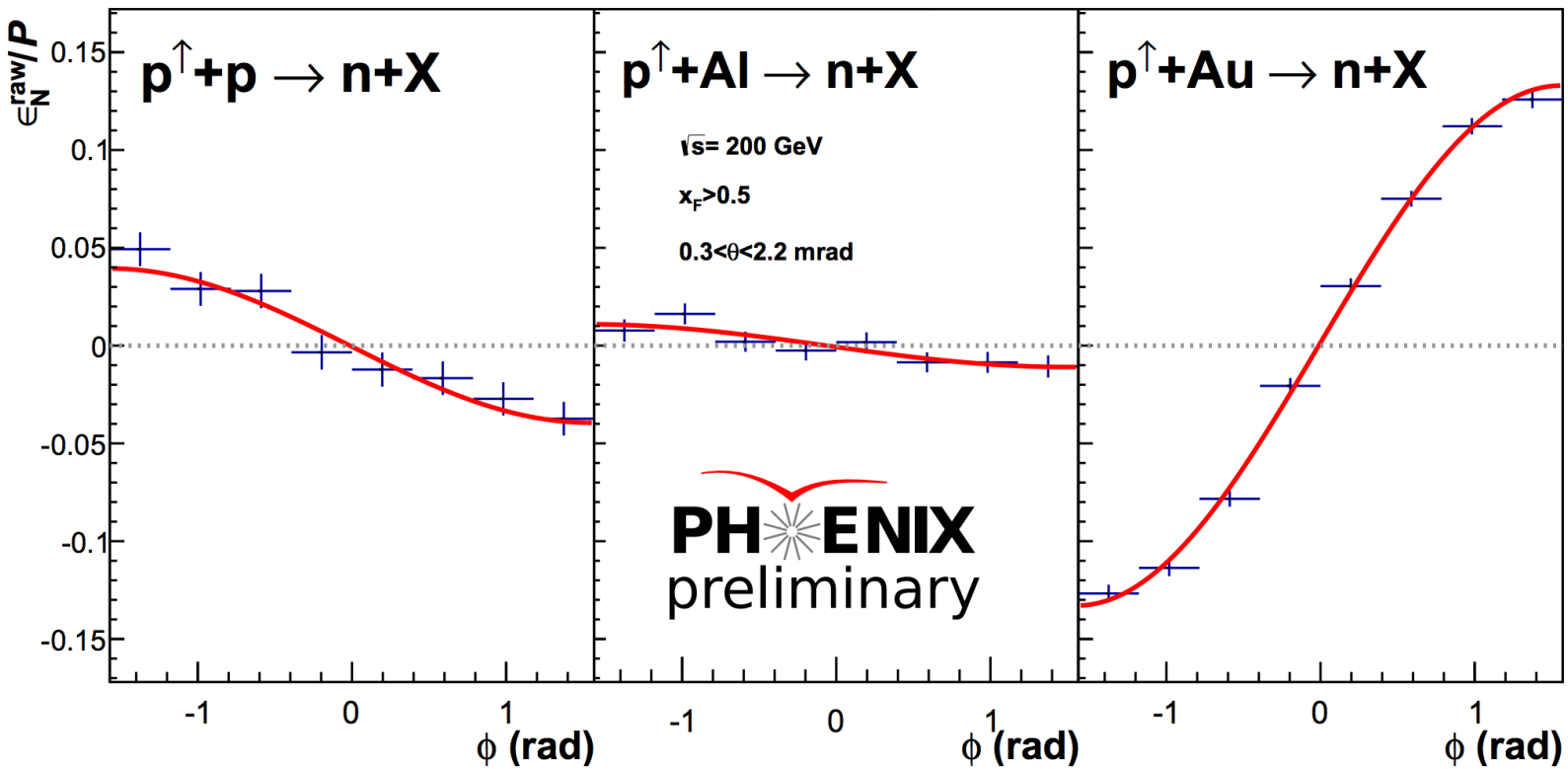
$$A_N = \frac{d\sigma_L^{\uparrow} - d\sigma_L^{\downarrow}}{d\sigma_L^{\uparrow} + d\sigma_R^{\uparrow}} = \frac{1}{P}\frac{N_L^{\uparrow} - R_{lum} N_L^{\downarrow}}{N_L^{\uparrow} + R_{\det} N_R^{\uparrow}}, \quad R_{lum} = \frac{L^{\uparrow}}{L^{\downarrow}}$$

- Square root formula: cancels acceptance and luminosity effects

$$A_N = \frac{1}{P}\frac{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}$$

Run15: from pp to pA

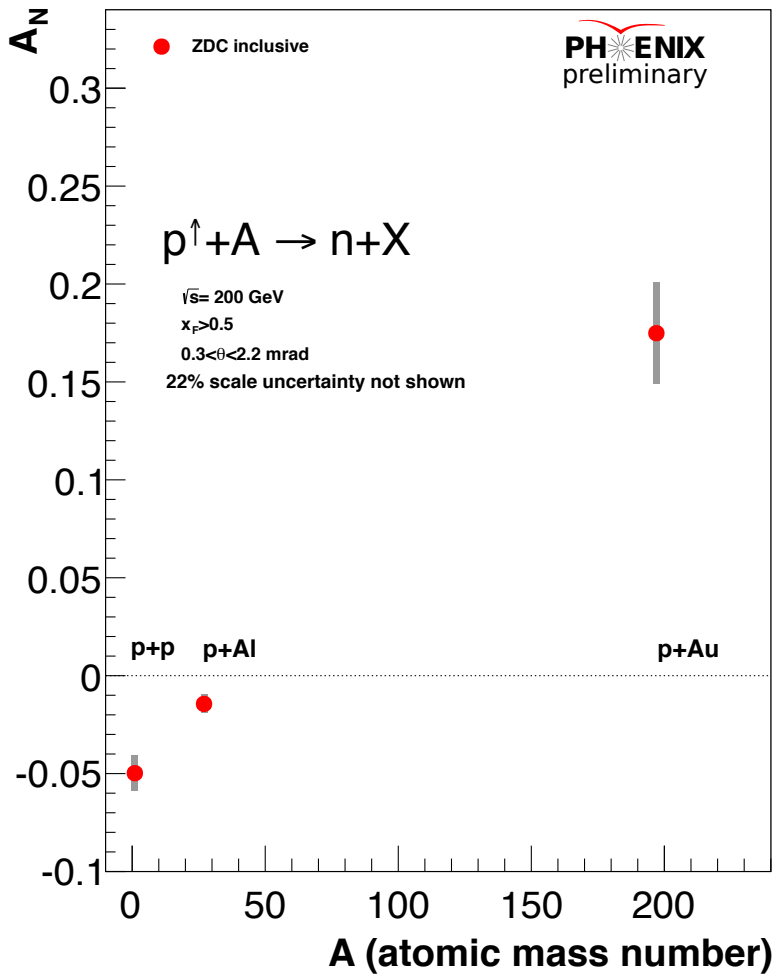
p+p *vs* p+Al *vs* p+Au

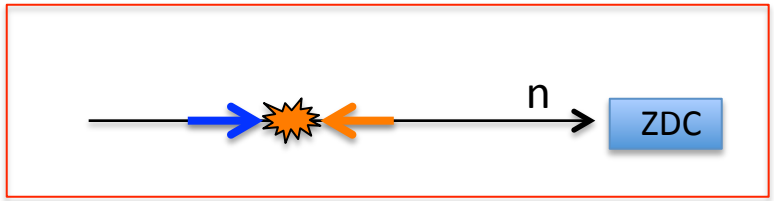


$A_N<0$ $A_N<0$ $A_N>0$

A_N vs nucleus mass

ZDC: η>6.5
BBC: 3.0<|η|<3.9





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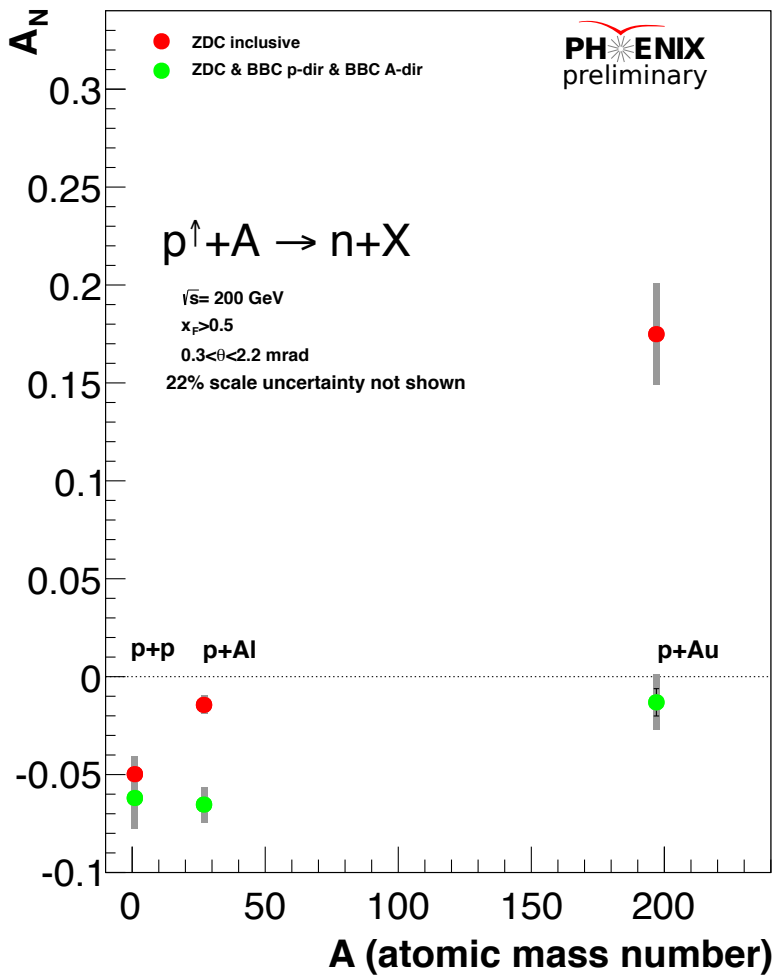

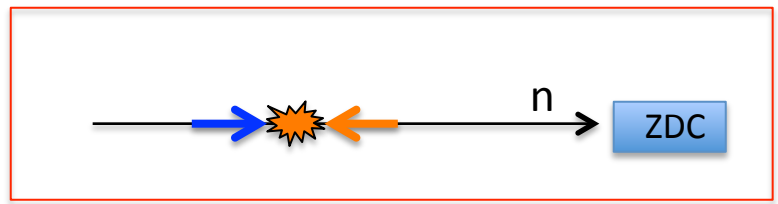

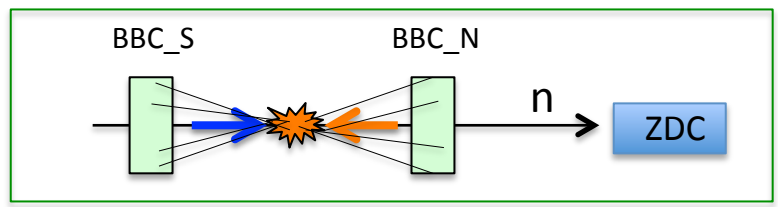

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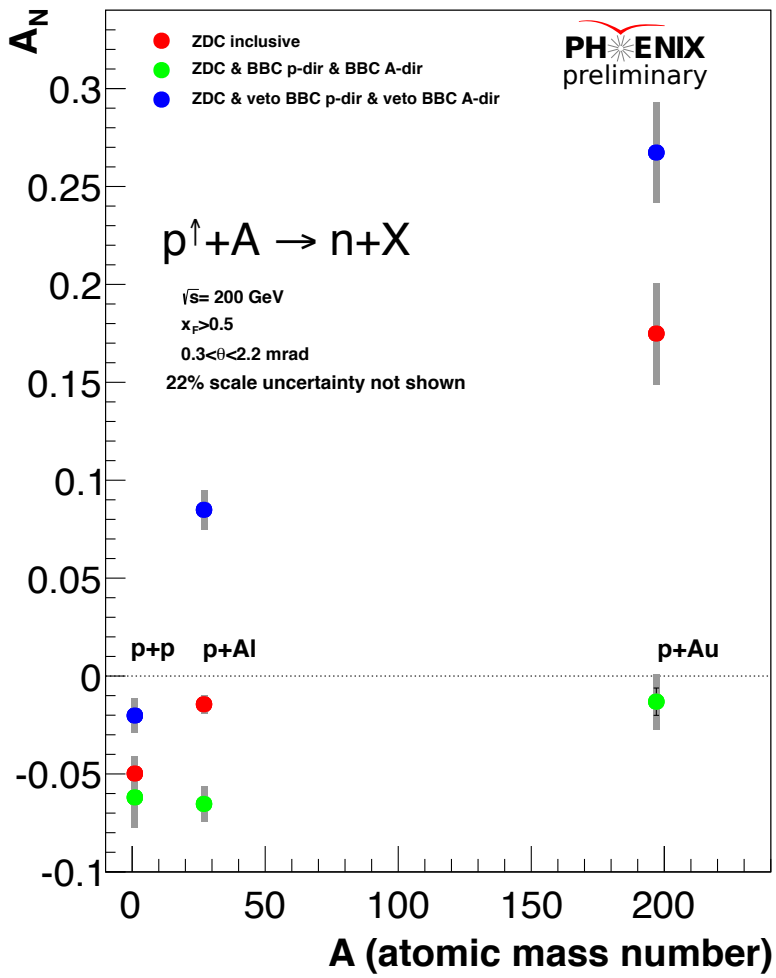
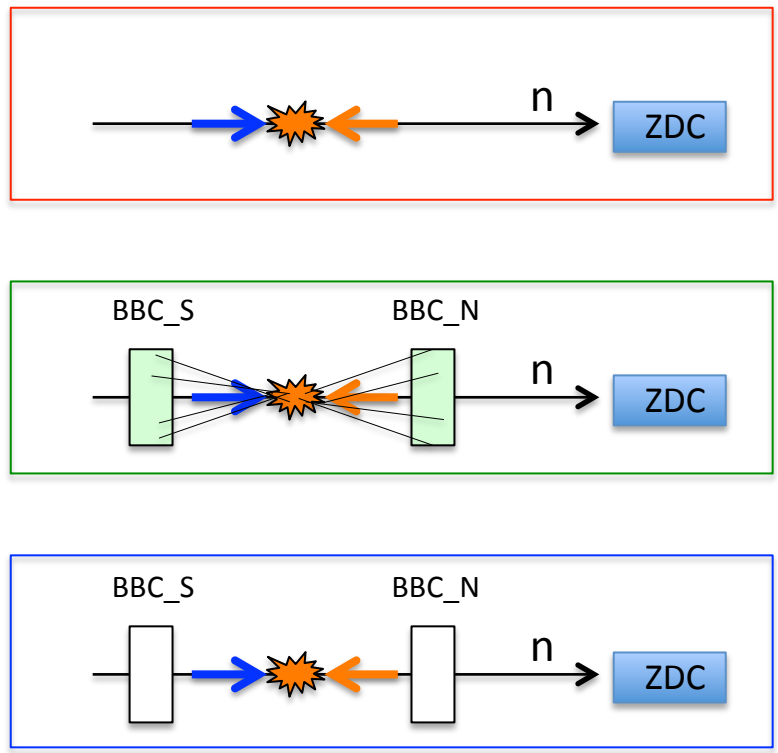
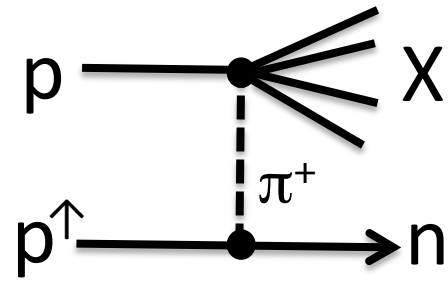




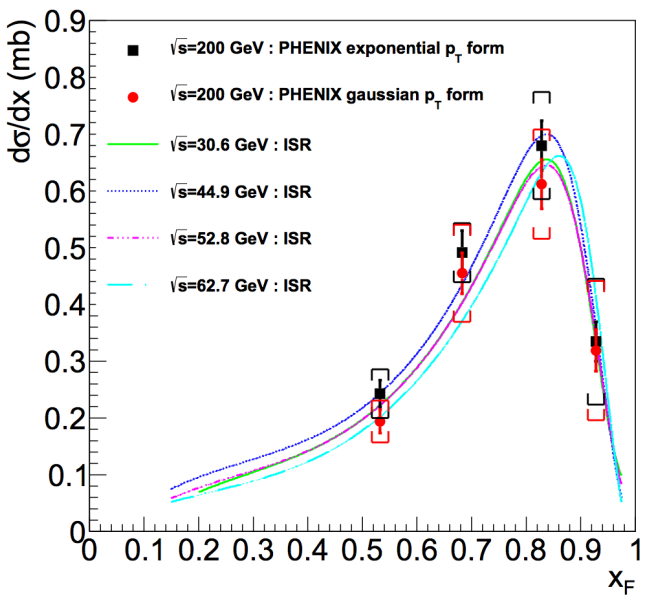
An attempt for Physics Interpretation

p_T<0.25 GeV/c (at $\sqrt{s}$=200 GeV) => pQCD not applicable

One Pion Exchange



PRD 88 (2013), 032006



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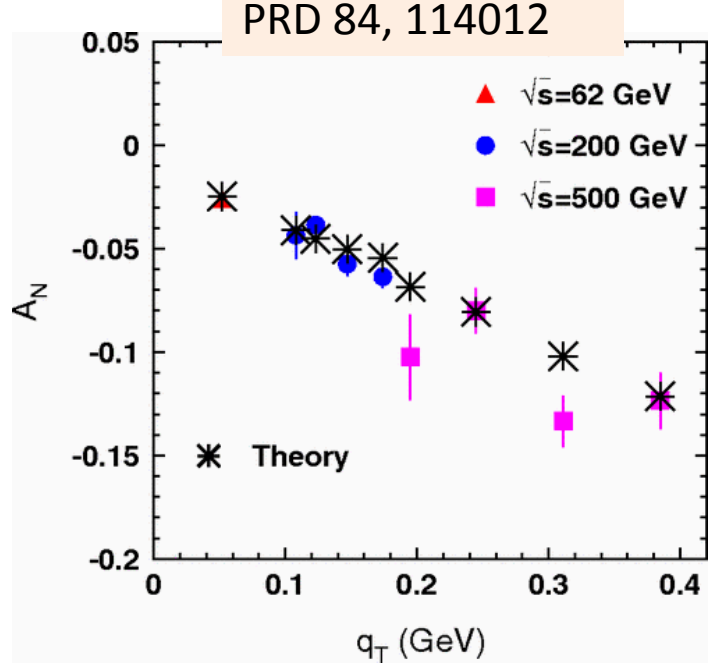


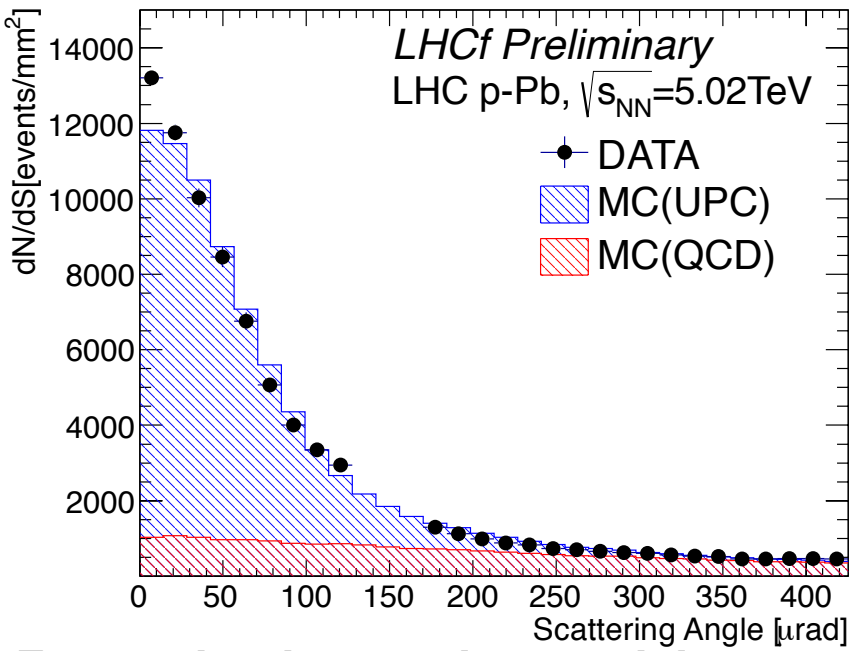
p+p: One Pion Exchange (OPE) model successful for both x-section and A_N

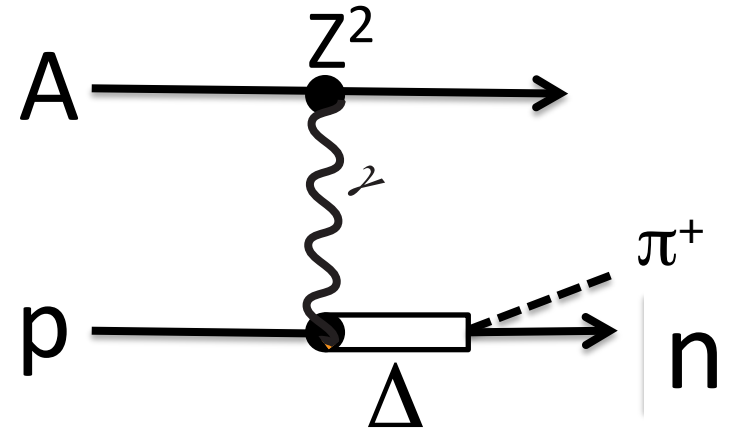
Does it work for p+A ?

Other mechanisms definitely exist, at least in p+A

Ultra Peripheral Collisions

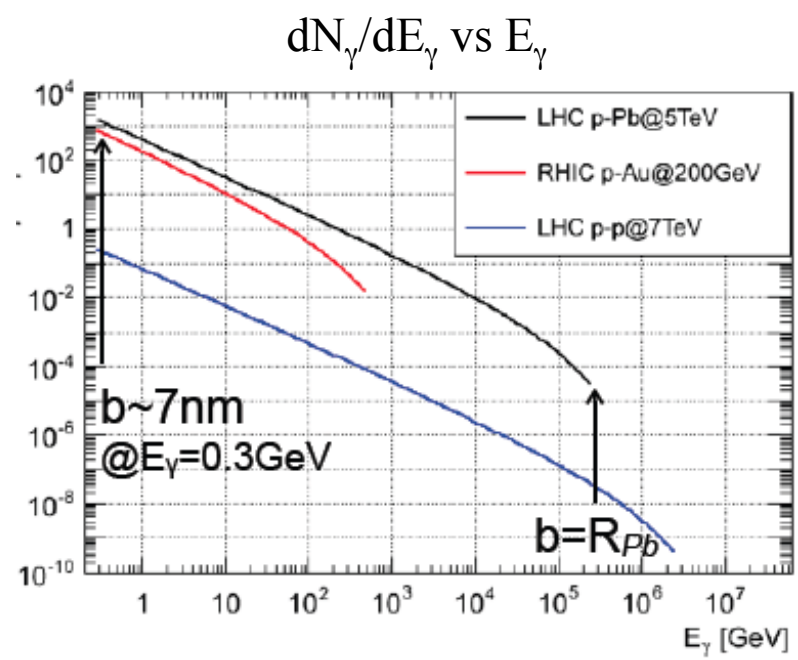
Hiroaki Menjo
HESZ-2015





Photon flux similar at LHC and RHIC

UPC – the dominant source of forward neutron production in p+A



QCD scattering

From Manabu Togawa's thesis

PYTHIA+GEANT simulation, E_{ZDC} > 5 GeV

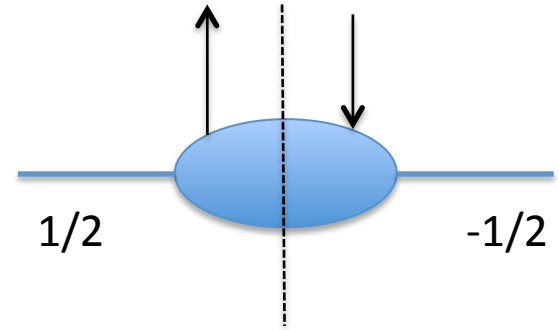
Physics process	Neutron (μb)
$qq \to qq$	35
$q\bar{q} \to q\bar{q}$	<1
$q\bar{q} \to gg$	<1
$qg \to qg$	268
$gg \to q\bar{q}$	9
$gg \to gg$	352

PYTHIA: 30% of neutron production in pp in ZDC acceptance

Mainly from gluon scattering

Δ^0, Δ^+, Δ^-, Λ^0 –> n

A_N



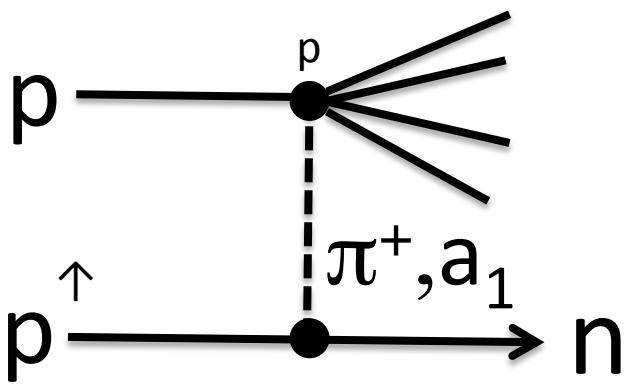
Needs interference between helicity flip and helicity non-flip amplitudes

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle + i|-\rangle\right) \qquad |\uparrow\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle - i|-\rangle\right)$$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \mathrm{Im}\left(M^{*}_{Non-Flip} \cdot M_{Flip}\right)$$

A_N: One Pion Exchange

Interference between π and a_1 Reggeon exchange



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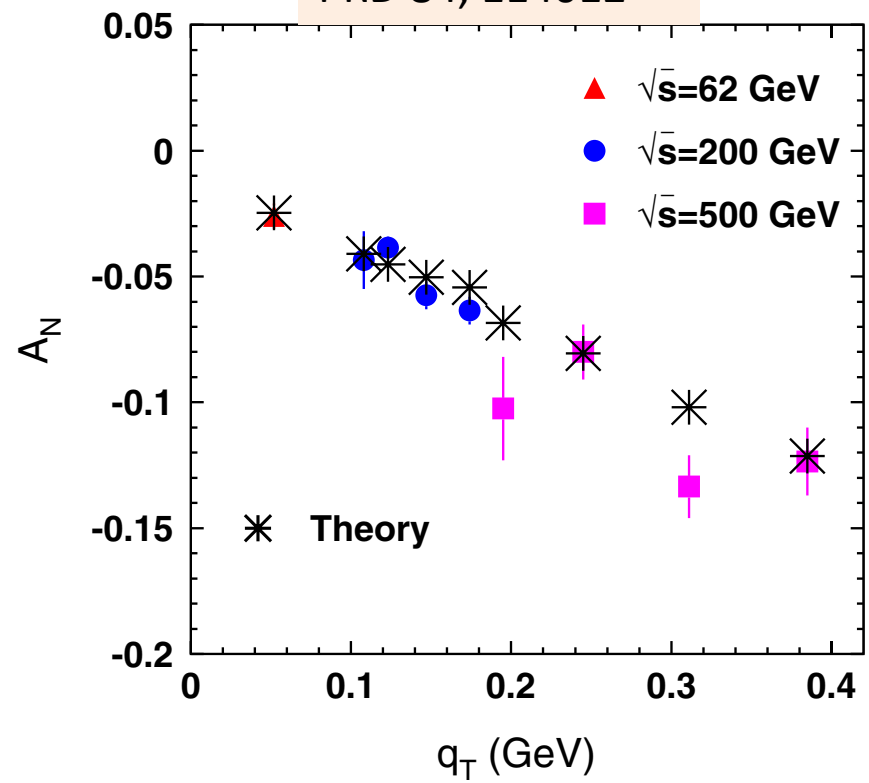
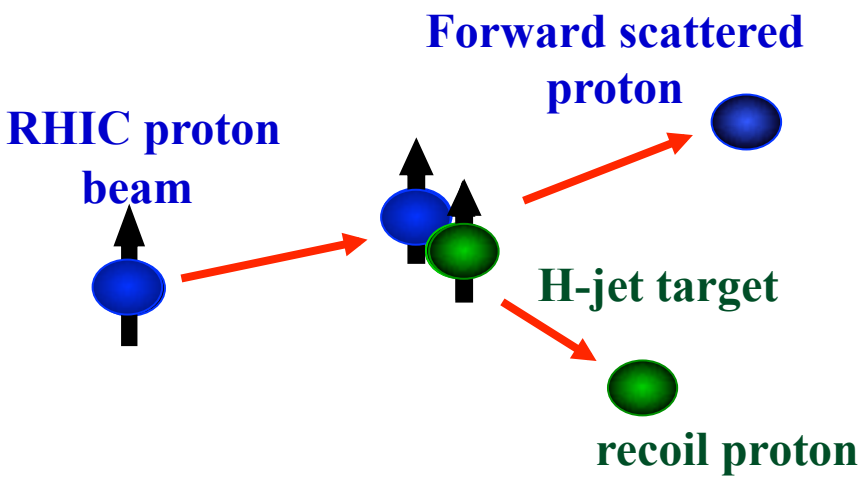
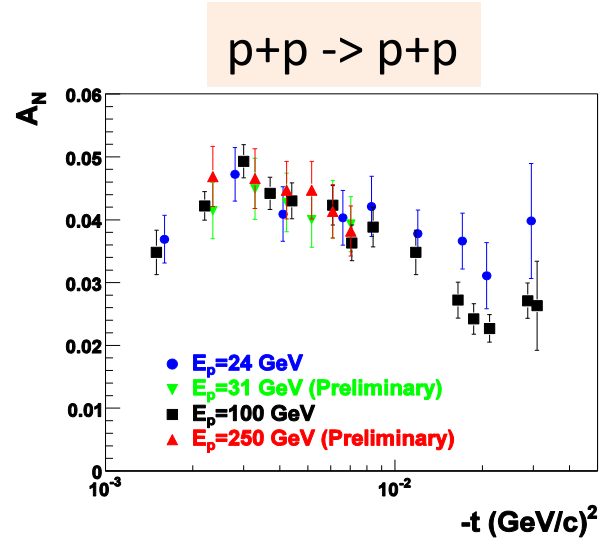
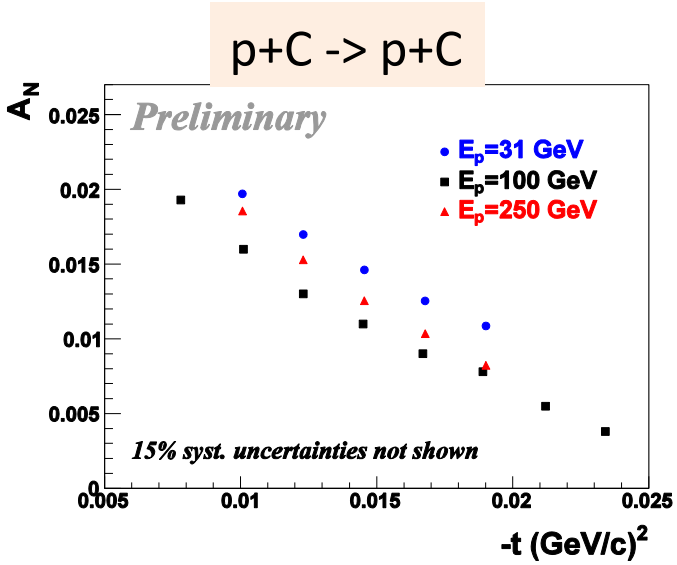


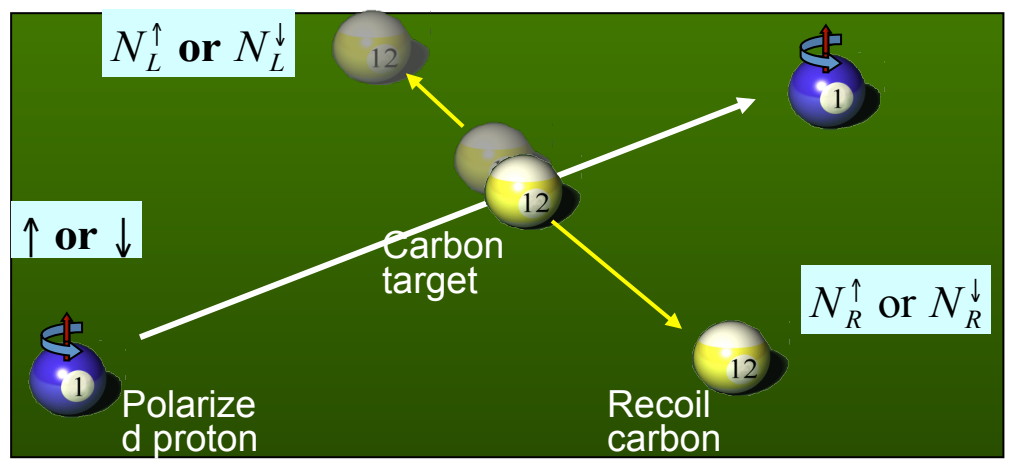
Coulomb−Nuclear Interference(CNI)

Interference between electromagnetic and hadronic amplitudes in the Coulomb-Nuclear Interference (CNI) region



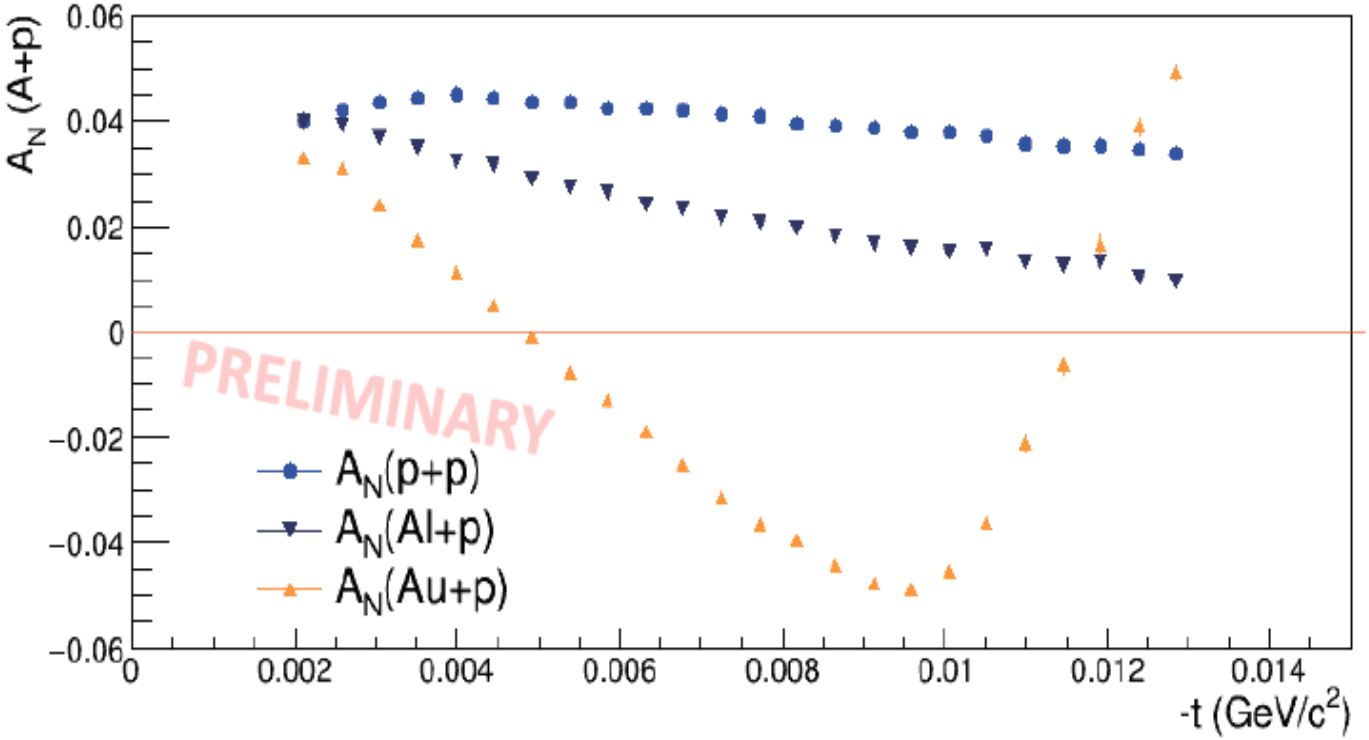






New CNI measurements from Run15

Run15 Hjet results: Oleg Eyser (PSTP-2015 workshop)



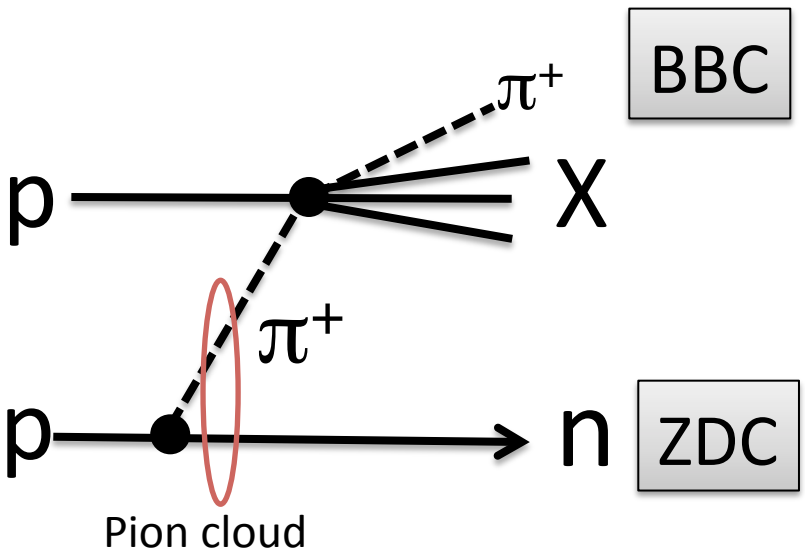
Fixed target with 100 GeV p(A) beam

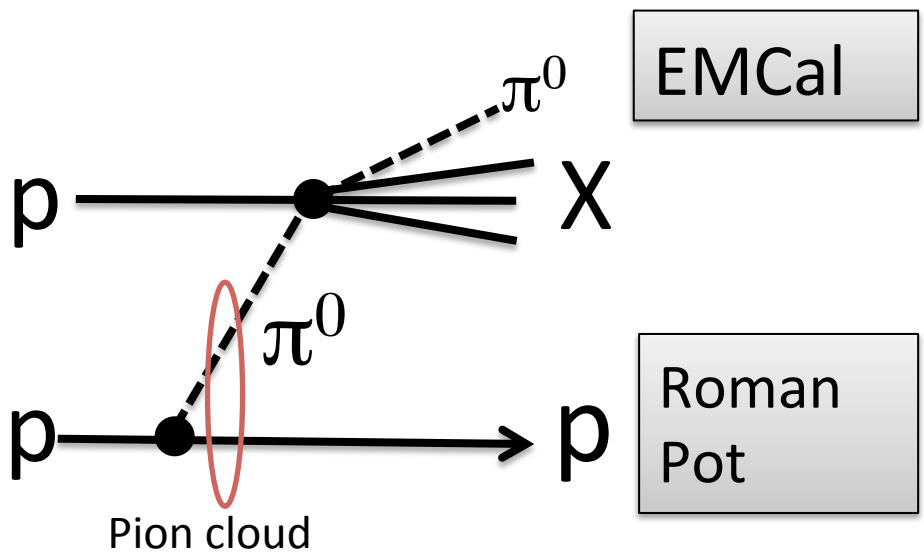
Forward neutron measurements are at t~0.02 - 0.5 (GeV/c) ^{2}

Also strong A-dependence

Connection to pion A_N ?

Diffractive process with pion exchange

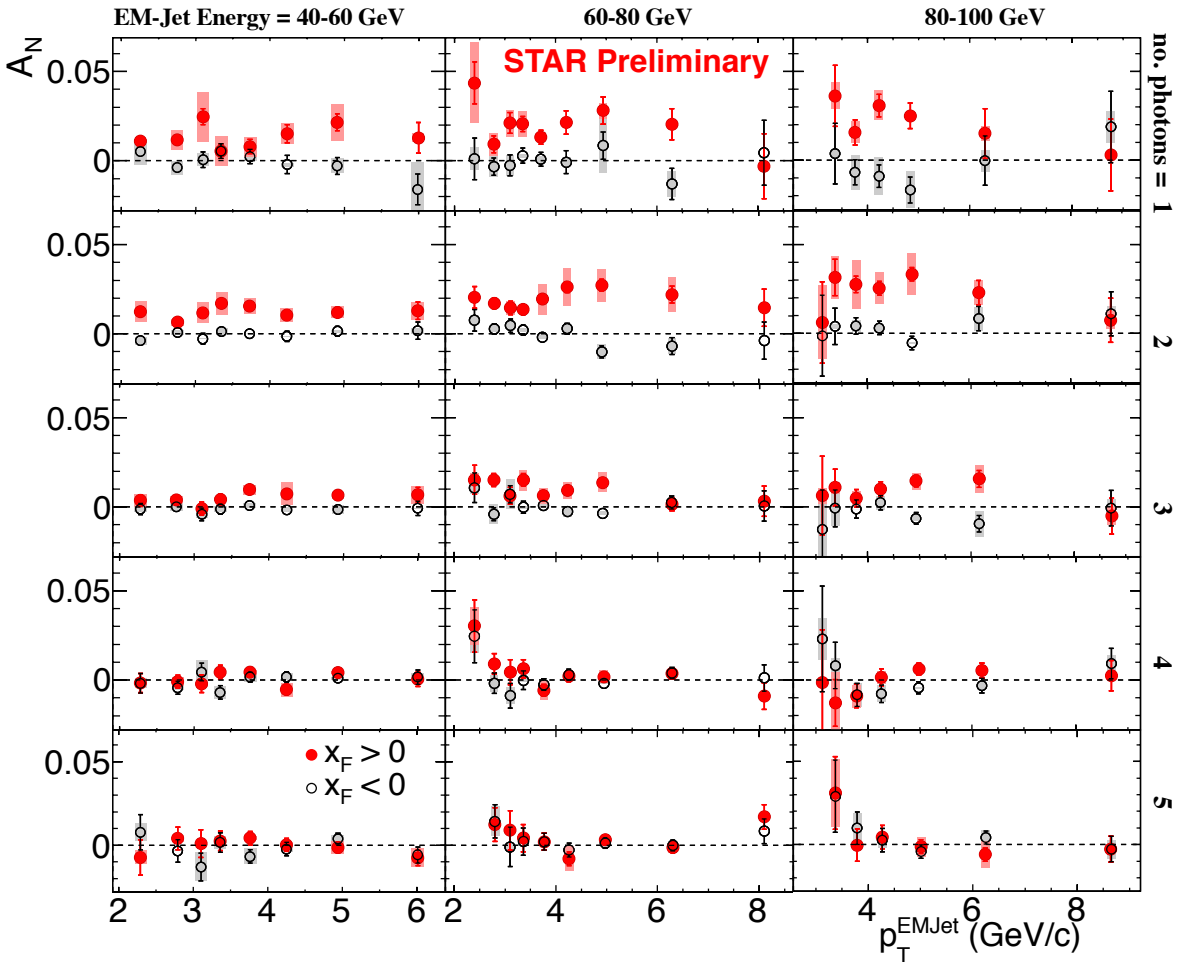




$A_N(n) \longleftrightarrow A_N(\pi^+)$

$A_N(p) \longleftrightarrow A_N(\pi^0)$

STAR: pp→π^0 X



Largest A_N for isolated $\pi 0$

Smaller A_N for more complex events (more activity around $\pi 0$)

Smaller A_N with away side jet present

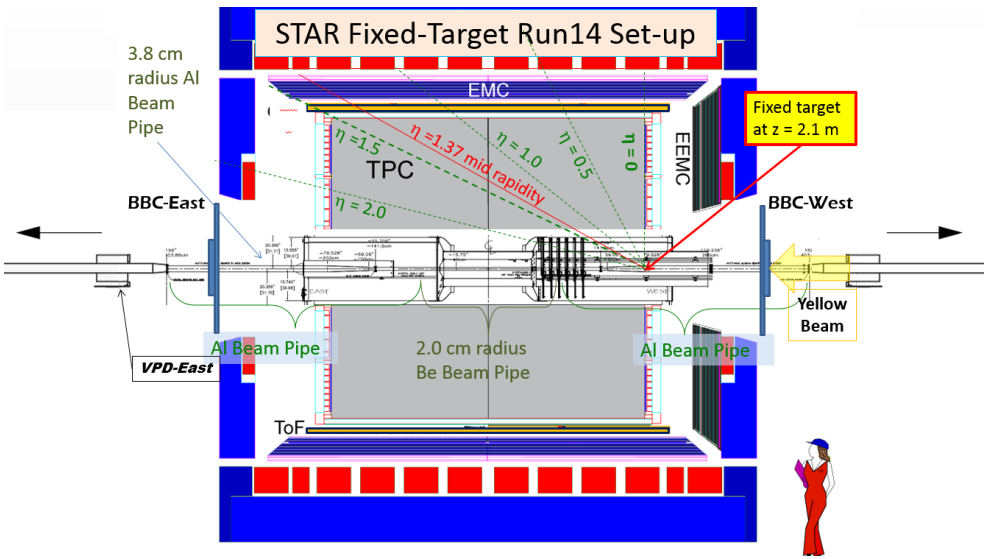
Does A_N come from 2→2 scattering?

May A_N come from hard diffraction:
$p\uparrow + p \rightarrow \pi^0 + p' + X$

STAR has already collected data in 2015 with Roman Pots to tag forward scattered p

Future Measurements?

Nuclear mass dependence (more species), energy dependence, correlations



Before 2020:

PHENIX decommissioned after 2016

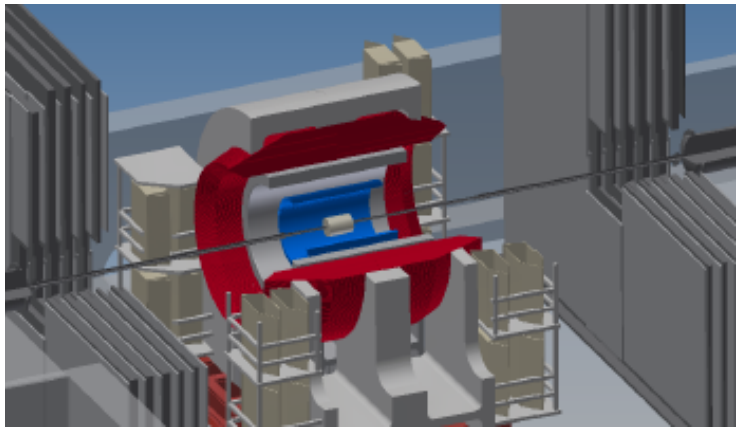
No plans for pA collisions

STAR fixed target in 2017?

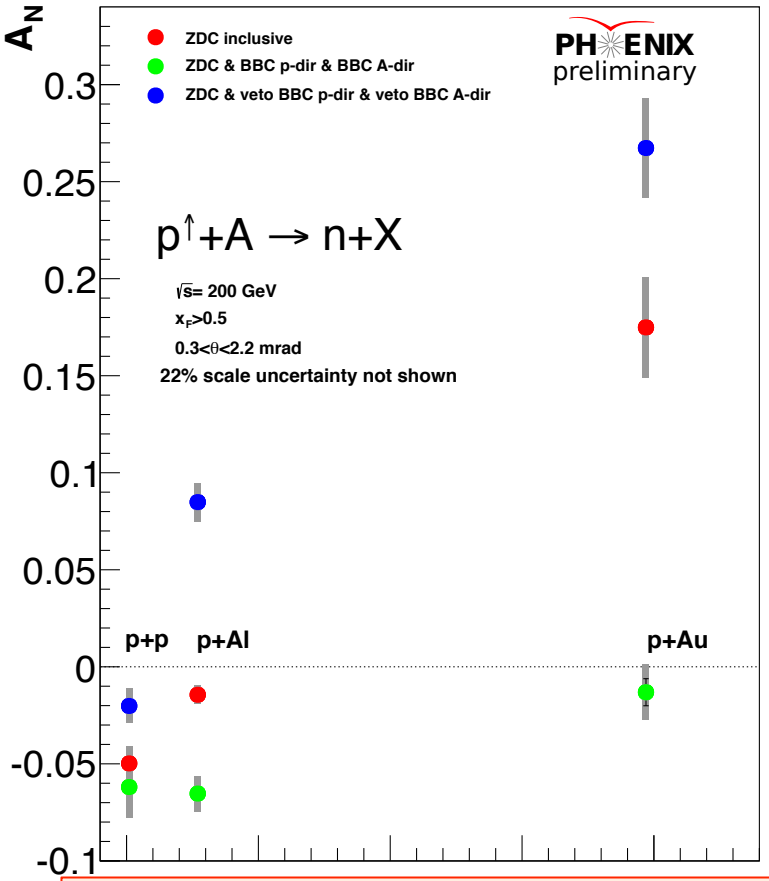
After 2020:

Plan to get more pA data

sPHENIX & STAR



Summary



A_N of forward neutron production: from pp to pA

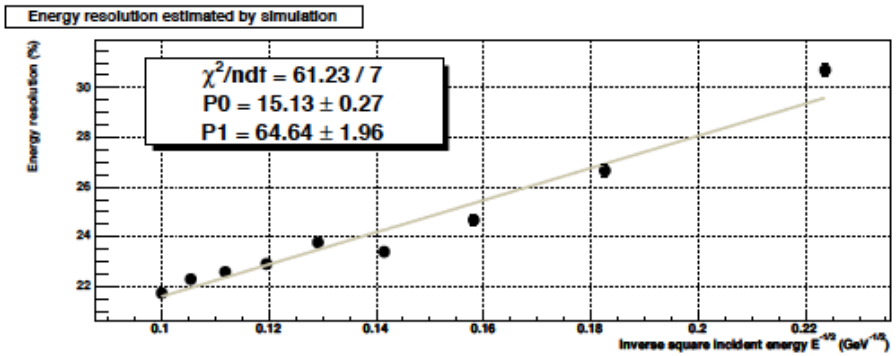
- Strong dependence on nucleus mass (or Z?) and particle production in other rapidity regions
- Likely multiple mechanisms contribute
- Saturation or compensation?
- QED or/and high parton density effect?
- Good to measure nuclear mass dependence (more species) and √s dependence

Need theoretical input !

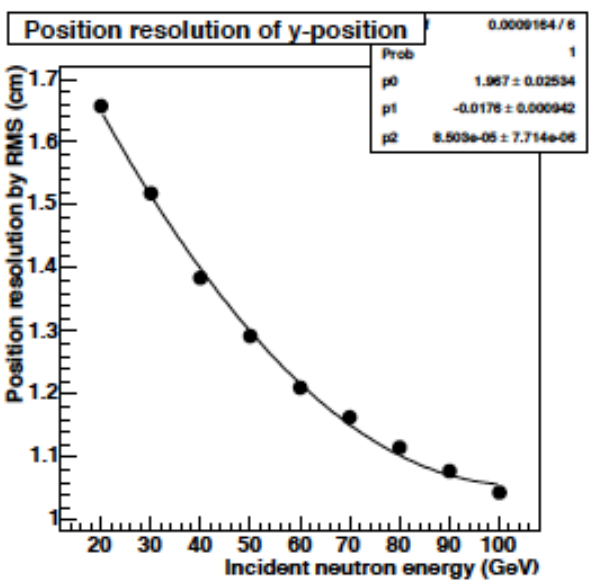
Great thanks to CAD for providing us with dedicated stores for these measurements,
And STAR collaboration for agreeing with providing us with these dedicated stores

Backup

Energy and Position Resolution

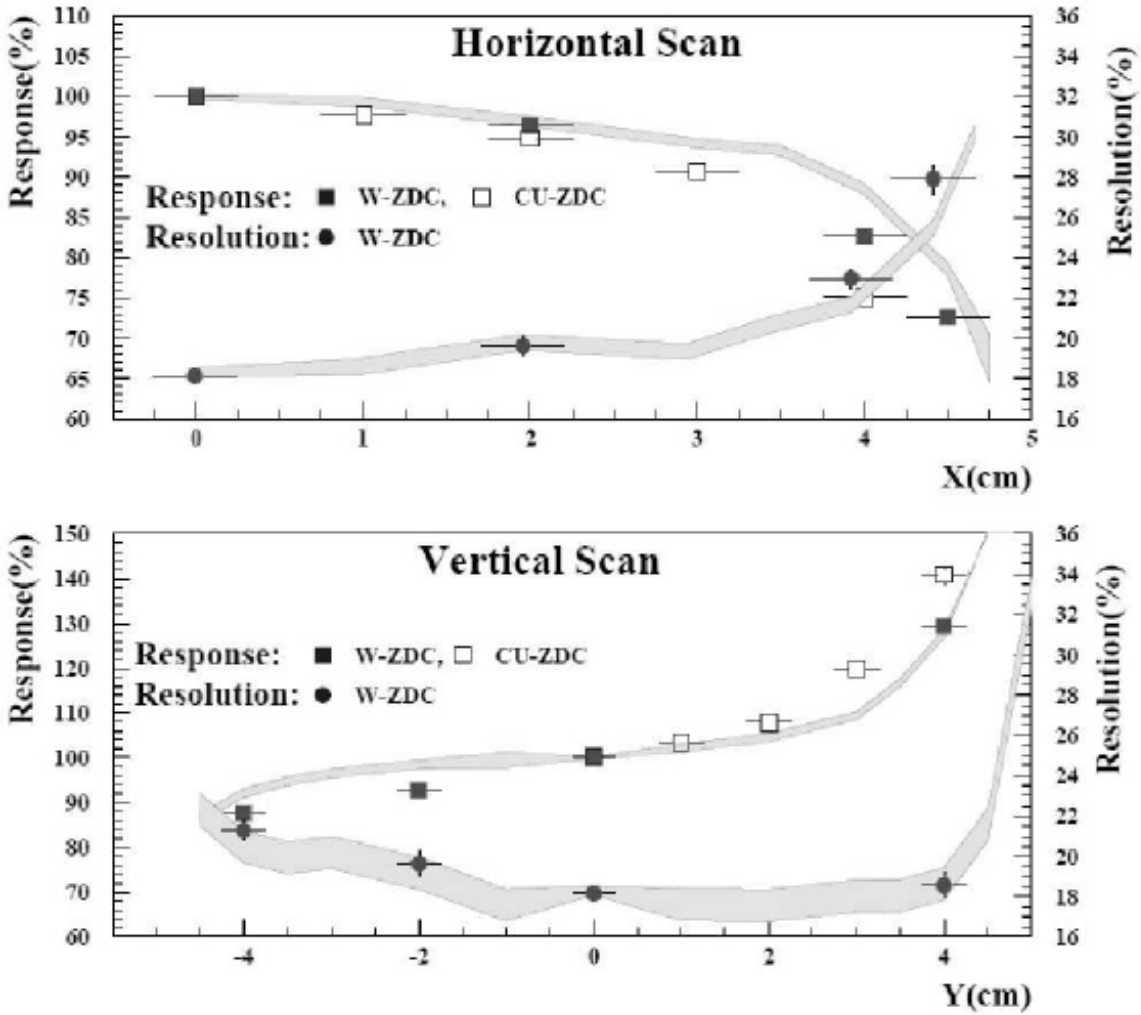


$$\frac{\Delta E}{E} = \frac{64.64}{\sqrt{E\ (\mathrm{GeV})}} + 15.13\ (\%).$$



$$\Delta x, y = \frac{5.1}{\sqrt{E(GeV)}} + 0.5\ (cm)$$

ZDC energy leakage at edges



Contributors to ZDC events

From Manabu Togawa's thesis

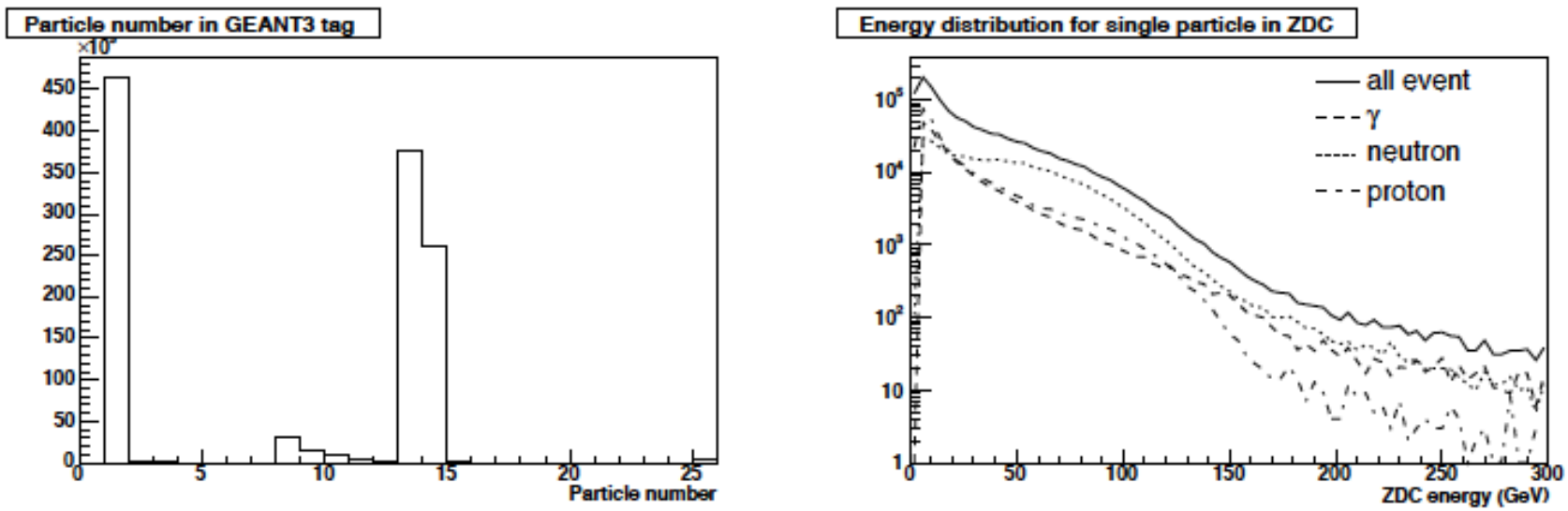


Figure 6.21: The event structure which is detected with the ZDC in pp collision at $\sqrt{s}$=200 GeV was studied by GEANT3 with PYTHIA simulation. The ZDC threshold has set to 5 GeV in the similar to the ZDCN|S trigger. Here, I show the event that one particle is detected with the ZDC in each pp collision (about 92%). The particle tag-number in GEANT3 (summarized in Table 6.1) is plotted in the left. Major particles, the photon, neutron and proton are shown as the tag-number = 1, 13 and 14, respectively. Measured energy distributions for these three particles with the ZDC are plotted in the right figure.

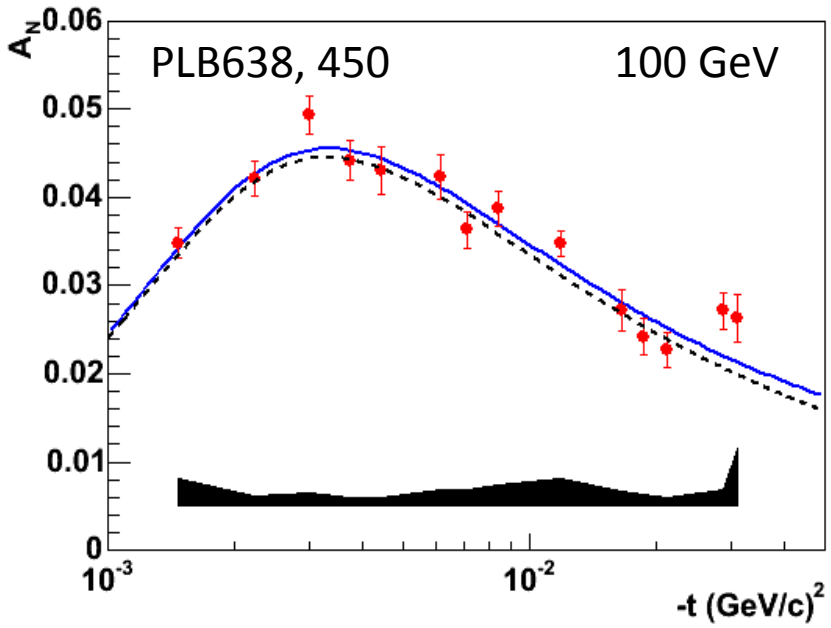
Contributors to ZDC events

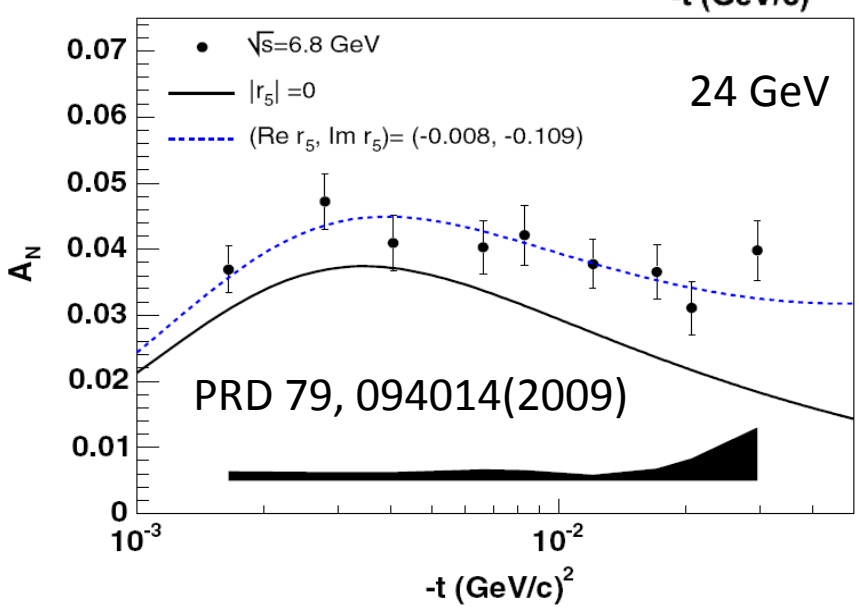
From Manabu Togawa's thesis

Physics process	Neutron (μb)	γ (μb)	Proton (μb)
$qq \to qq$	35	46	14
$q\bar{q} \to q\bar{q}$	<1	<1	<1
$q\bar{q} \to gg$	<1	<1	<1
$qg \to qg$	268	358	95
$gg \to q\bar{q}$	9	12	3
$gg \to gg$	352	468	114
Elastic scattering	0	0	446
Single diffractive (XB)	<1	2	387
Single diffractive (AX)	462	527	107
Double diffractive	328	413	92
Low-p_T scattering	551	651	137
Total	2006	2479	1395

Table 6.2: Cross sections for major three particles detected with the ZDC in each physics process studied by GEANT3 with PYTHIA. Same energy threshold as ZDCN|S trigger, 5 GeV, was required.

HJet: A_N in pp





$$A_N \approx \mathrm{Im}\left(\phi_{SF}^{em}\phi_{NF}^{had} + \phi_{SF}^{had*}\phi_{NF}^{em}\right) \Big/ \left|\phi_{NF}^{had}\right|^2$$

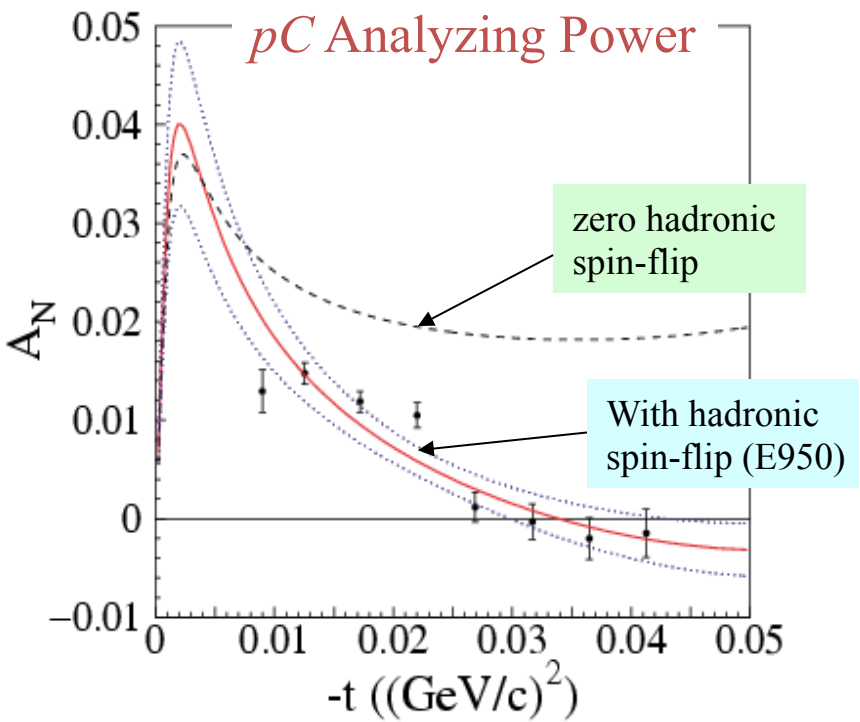
100 GeV: calculations with no hadronic spin flip amplitude contribution are consistent with data

24 GeV: calculations with no hadronic spin flip amplitude contribution are not consistent with data

pC: A_N

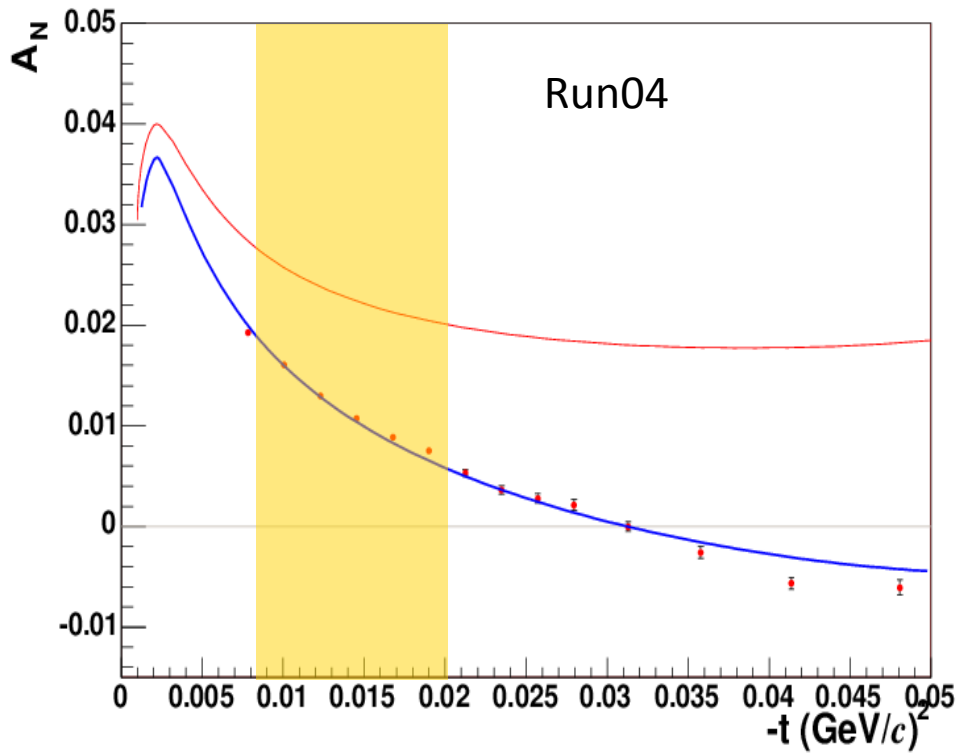
Elastic scattering: interference between electromagnetic and hadronic amplitudes in the Coulumb-Nuclear Interference (CNI) region

$$A_N \approx C_1 \phi_{flip}^{em\,*} \phi_{non-flip}^{had} + C_2 \phi_{non-flip}^{em\,*} \phi_{flip}^{had}$$



Phys.Rev.Lett.,89,052302(2002)

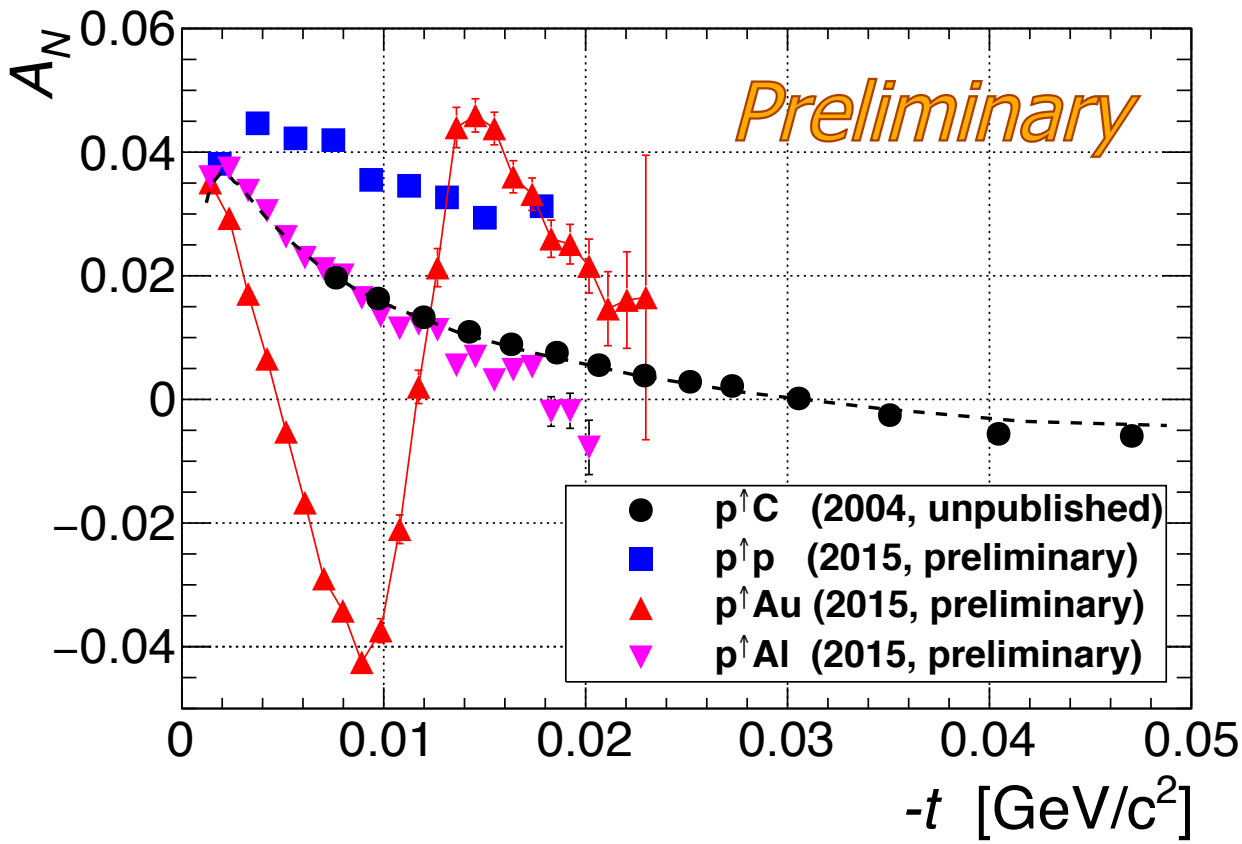
E_{beam} = 21.7GeV



unpublished

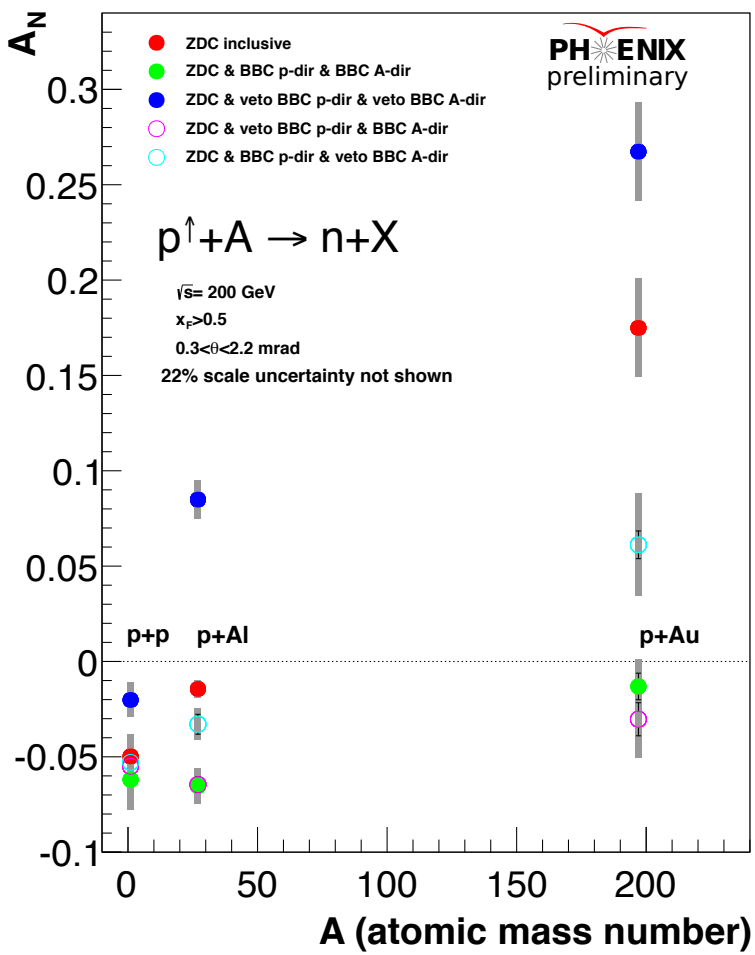
E_{beam} = 100 GeV

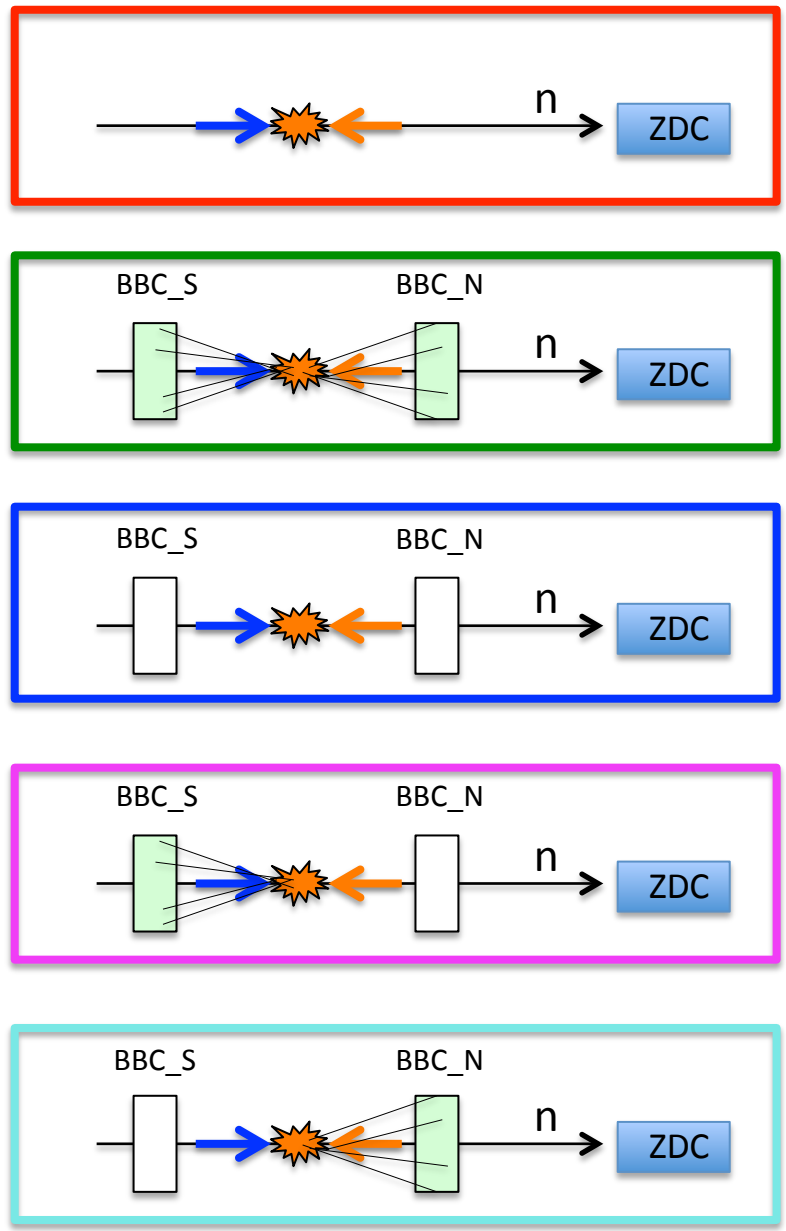
CNI


A_N
0.06
0.04
0.02
0
−0.02
−0.04
0
0.01
0.02
0.03
0.04
0.05
-t [GeV/c²]
Preliminary
p↑C (2004, unpublished)
p↑p (2015, preliminary)
p↑Au (2015, preliminary)
p↑Al (2015, preliminary)

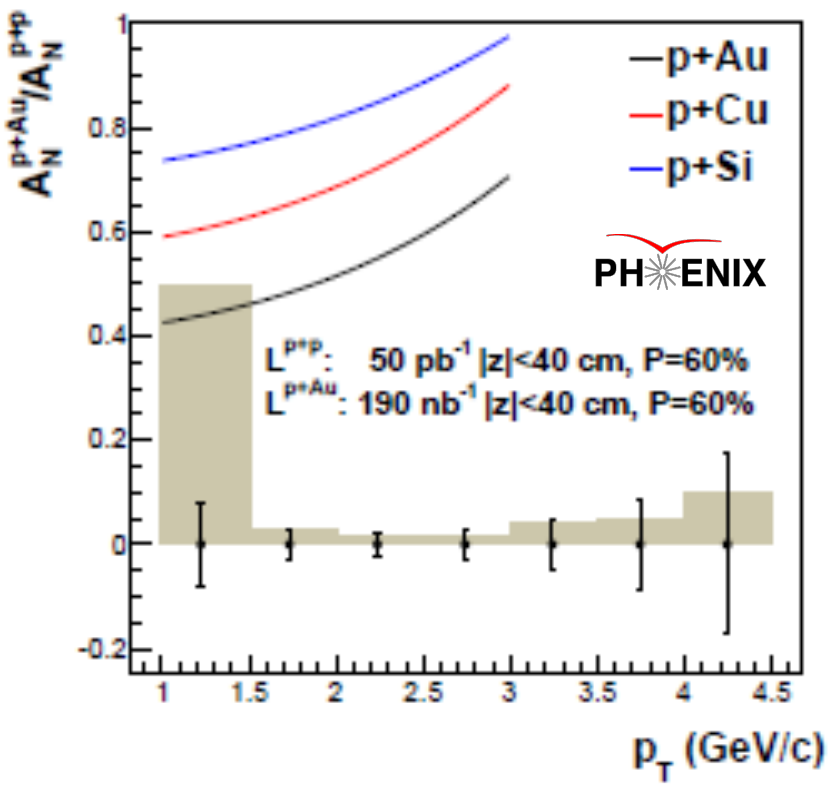
ZDC: η>6.5

BBC: 3.0<|η|<3.9





π0 A_N in pA



Probing gluon saturated matter, Color Glass Condensate (CGC) with polarized protons

Kang, Yuan: PRD84, 034019
Kovchegov, Sievert: PRD86, 034028

- Unique RHIC possibility $p^{\uparrow}A$
- Synergy between CGC based theory and transverse spin physics
- Suppression of A_N in $p^{\uparrow}A$ provides sensitivity to Q_s
- Data already collected in Run-2015!